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Rheological implications of the internal structure and crystal fabrics of the West Antarctic ice sheet as revealed by deep core drilling at Byrd Station

Cover: Crystalline texture and c-axis fabric variations
within the Antarctic ice sheet at Byrd Station.

CRREL Report 76-35

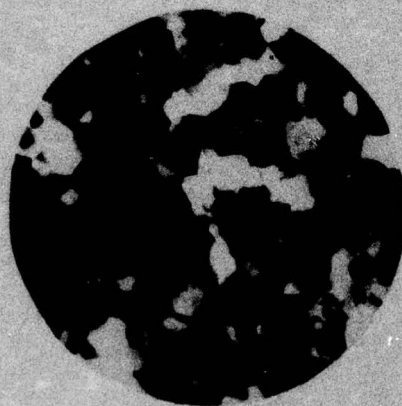*Rheological implications of the internal structure and crystal fabrics of the West Antarctic ice sheet as revealed by deep core drilling at Byrd Station*

Anthony J. Gow and Terrence Williamson

September 1976

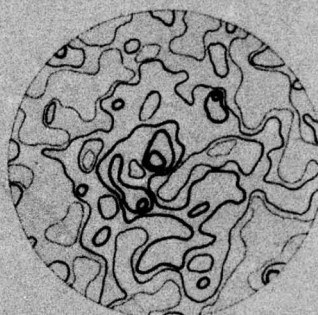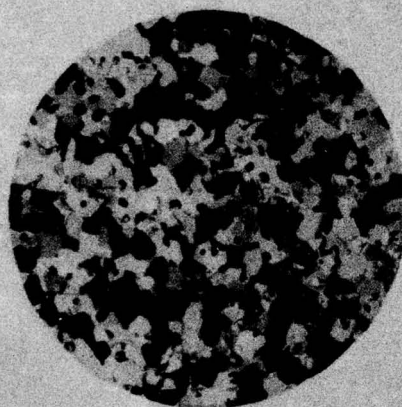| REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
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Crystalline textures and fabrics of ice cores from the 2164-m-thick ice sheet at Byrd Station, Antarctica, reveal the existence of an anisotropic ice sheet. A gradual but persistent increase in the c-axis preferred orientation of the ice crystals was observed between the surface and 1200 m. This progressive growth of an oriented crystal fabric is accompanied by a 20-fold increase in crystal size between 56 and 600 m, followed by virtually no change in crystal size between 600 and 1200 m. A broad vertical clustering of c-axes develops by 1200 m. Between 1200 and 1300 m the structure transforms into a fine-grained mosaic of crystals with their basal glide planes now oriented substantially within the horizontal. This highly oriented fine-grained structure, which persists to 1800 m, is compatible only with

20. Abstract (cont'd).

a strong horizontal shear deformation in this part of the ice sheet. Rapid transformation from single- to multiple-maximum fabrics occurs below 1800 m. This transformation, accompanied by the growth of very large crystals, is attributed to the overriding effect of relatively high temperatures in the bottom layers of old ice at Byrd Station rather than to a significant decrease in stress. The zone of single-maximum fabrics between 1200 and 1800 m also contains numerous layers of volcanic dust. Fabrics of the very fine-grained ice associated with these dust bands indicate the bands are actively associated with shearing in the ice sheet. Some slipping of ice along the bedrock seems likely at Byrd Station, since the basal ice is at the pressure melting point and liquid water is known to exist at the ice/rock interface. The textures and fabrics of the ice indicate that plastic deformation (intracrystalline glide) in the zone of strong single-maximum fabrics, and movement of ice along discrete shear planes situated well above bedrock, are also major contributors to the flow of the ice sheet. Any extensive shearing at depth could seriously distort stratigraphic records contained in the ice cores, such as climatic history inferred from stable isotope analysis. Also, the common practice of using simplified flow models to approximate the depth-age relationships of deep ice sheet cores may need to be revised in light of the deformational features and fabrics observed in the Byrd Station ice cores.

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RHEOLOGICAL IMPLICATIONS OF THE INTERNAL STRUCTURE AND CRYSTAL FABRICS OF THE WEST ANTARCTIC ICE SHEET AS REVEALED BY DEEP CORE DRILLING AT BYRD STATION

Anthony J. Gow and Terrence Williamson

INTRODUCTION

During 1968 a core hole was drilled to the bottom of the Antarctic Ice Sheet at Byrd Station (Ueda and Garfield 1970, Gow et al. 1968). Holes in the range 100 to 400 m had been drilled previously in Antarctica (Schytt 1958, Bogoslovsky 1958, Patenaude et al. 1959, Ragle et al. 1960), including the first successful drilling of an Antarctic ice shelf (Ragle et al. 1960), but this latest drilling at Byrd Station marked the first complete penetration of the thick inland ice sheet of Antarctica (see Fig. 1). The vertical thickness of ice drilled was 2164 m. Cores measured 10.8 cm in diameter and core recovery amounted to 99.7%.

The deep drilling at Byrd Station represented part of a much larger investigation of the glaciological characteristics of a portion of the ice sheet of west Antarctica. A major objective of the drilling was to complement surface glaciological and geophysical measurements (Whillans 1973, Dewart et al. 1974, and Whillans 1975) and airborne radio exploration of the ice sheet (Robin et al. 1970) around and up the flow line from Byrd Station.

Details of the drilling techniques are given in Ueda and Garfield (1970) and preliminary results of core studies are presented in Gow et al. (1968) and in Gow (1970a). More specific investigations of the physical and geochemical properties of the cores are reported
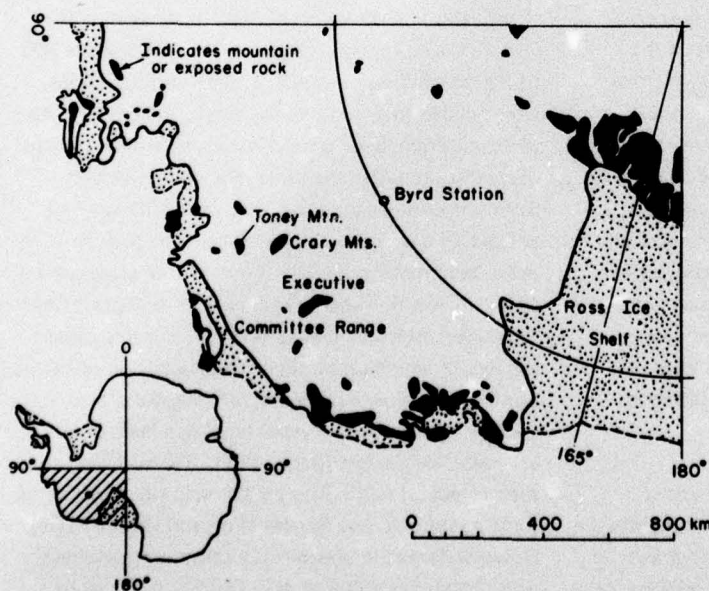

Figure 1. Location map of deep core drilling site at Byrd Station, Antarctica. The mountains north of Byrd Station include recently active volcanoes which were probably the primary sources of numerous ash and dust bands found in the cores.

in Epstein et al. (1970), Gow (1971a), Gow and Williamson (1971), Johnsen et al. (1972), Thompson (1973) and Gow and Williamson (1975). Results of preliminary examinations of the crystal texture and fabrics of the Byrd Station cores are given in Gow (1970a and 1971b).

The deep coring at Byrd Station was in essence an extension of a drilling program initiated in 1957 at Old Byrd Station during the International Geophysical Year (IGY). Cores from this earlier drill hole at Old Byrd Station (located about 10 km west of the deep drill site at Byrd Station), and from a hole drilled through the Ross Ice Shelf at Little America V in 1958 (Gow 1963), revealed variations in ice structure and fabrics that clearly reflected significant differences between the thermal and deformational histories of the two ice columns. It was anticipated, on the basis of these earlier results (Gow 1970b), that the onset of shear in the deeper parts of the ice sheet at Byrd Station should lead to an oriented crystal fabric. Comprehensive analyses of cores from the 2164-m thick ice sheet at Byrd Station not only confirm this prediction, but they also reveal a degree of crystal anisotropy not previously observed in other glaciers.

ANALYTICAL PROCEDURES

The present observations on ice crystal texture and fabrics are based largely on thin sections of ice cores cut either parallel or normal to the long axis of the cores.* Samples approximately 1 cm thick were frozen onto glass plates and then sectioned on a microtome. Finished sections, measuring 0.1 cm or less in thickness (depending upon crystal size), were examined on the Rigsby stage, an enlarged version of the conventional 4-axis universal stage and designed especially for the larger crystals found in glaciers. Photographs of the thin sections were obtained with a press camera (10×12.5 cm) mounted directly above the Rigsby stage. Most measurements on thin sections were conducted at –10°C. Cores and sections were stored at

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* In this report fabric is restricted to the oriented features observed in ice cores, e.g., crystal elongation, bubble alignment and c-axis orientations. Features such as the sizes and shapes of crystals and bubbles are described as texture.

–30°C to minimize sublimation, and periodic inspections of thin sections over the past five years have failed to disclose any changes in crystal texture or fabric.

Crystal size

Crystal size was obtained from measurements of the number of crystals in given areas of thin-section photographs. As many as 500 crystals were counted in finer-grained ice from the upper layers of the ice sheet, but as few as 50 crystals had to suffice for the deepest cores (within 300 to 400 m of the bottom) where crystals grow to large size, and where size is further complicated by the branched nature of most of the crystals.

Crystal orientation

The crystallographic c-axis in ice corresponds to the optic axis, so that the orientations of individual crystals are readily obtained on the Rigsby stage. The technique, essentially the same as that used to study quartz fabrics, is described in Langway (1958).

Ice fabrics and related parameters were investigated at 50 different levels in the ice sheet. Several hundred thin sections were prepared and the optic axes [0001] of more than 10,000 crystals were measured. Most of the measurements were obtained on sections cut normal to the long axis of the core. A single section usually contained enough crystals for a statistically significant determination of the c-axis fabric at that level. In very coarse-crystal ice from the bottom 300 to 400 m of core, however, as many as 30 sections were needed to determine the fabric. These sections of coarse-grained ice were cut from unbroken lengths of core (to preserve the same relative orientation from one core piece to the next), and a distance of at least 15 cm was maintained between sections in order to minimize the risk of cutting the same crystal twice. It was not uncommon to find the same branching crystal intersected at several places in the same section, in which case a single determination of the c-axis orientation was used in plotting the fabric. Complexly branched crystals have also been observed in temperate glaciers (Bader 1951, Rigsby 1968) and their effect on fabric interpretation is still a matter of some conjecture (see Rigsby 1968 and Hooke 1969). However, it would appear that a thorough examination of the crystalline texture of ice is essential to any rational interpretation of ice fabrics.

Core orientation

No deliberate attempt was made to orient ice cores in the azimuth during drilling. While drilling through the lower half of the ice sheet, however, a large number of volcanic dust bands, up to 6 cm thick, were encountered. These bands were always inclined 10 to 15° from the horizontal plane. Earlier in the drilling the hole had begun to deviate from the vertical, the inclination reaching as much as 15° in deeper parts of the hole. Inclinometer measurements were made at frequent intervals, and in all cases the inclination of the drill from the vertical corresponded within a degree or so of the angle at which the cloudy bands in the ice cores were inclined to the horizontal. This correspondence almost certainly implies that the primary attitude of the bands is close to horizontal.

OBSERVATIONS

Visible stratigraphic structures

Stratigraphic layering, resulting from variations in surface snow accumulation, persists to at least the depth of the snow-ice transition (56 m), but is substantially obliterated by recrystallization below 100 m. Careful analysis of the seasonal snow layers has yielded long-term records of accumulation, such as those obtained by Gow (1968) on cores from the Old Byrd Station drill hole. However, long-term trends and averages can now be established by other techniques, so that no attempt was made in the present instance to analyze annual stratigraphy. In deep cores from Byrd Station, visible stratigraphy is restricted to layers of moraine in the bottom 5 m of ice and to layers of volcanic ash and dust that occur abundantly in the lower half of the ice sheet.

Crystalline texture

Changes in ice texture with increasing depth are illustrated in Figure 2. Variations in the top 300 m are essentially the same as those observed in the earlier IGY drilling at Old Byrd Station (Gow 1970b). A minor difference is the depth to the snow-ice transition, which lies at about 56 m at the deep drill site.* This

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When interconnected pores in compacted snow pinch off to form individual bubbles, the snow is said to have transformed into bubbly glacier ice. This transition occurs at a density of about 0.83 Mg/m³, equivalent to an entrapped bubble volume of about 10%.

is appreciably shallower than the transition depth of 65 m at Old Byrd Station, but it is entirely consistent with the difference between snow accumulation at the two sites (Gow and Rowland 1965, Gow et al. 1972) and with independent estimates based on measurements of p-wave velocity (Kohnen and Bentley 1973).

The typically equant texture of crystals in fresh bubbly ice at 65 m at Byrd Station continues to a depth of 200 to 300 m before giving way to a texture of interpenetrating crystals. Porphyroblastic crystals (crystals abnormally large in relation to their neighbors) also begin to appear. A further characteristic of the texture is the gradual increase with depth of crystals exhibiting undulose or wavy optical extinction.

A major change in texture occurs between 1200 and 1300 m with a marked reduction in size of ice crystals. This fine-grained texture persists to just below 1800 m where it gives way completely to very large, branched crystals in the bottom 350 m of ice. These large crystals are characterized by smoother boundaries between crystals and by the disappearance of much of the undulose extinction exhibited by crystals in the overlying ice.

Air bubbles

Air bubbles trapped in the ice at Byrd Station constitute an important element of the texture. Approximately 220 bubbles/cm³ are sealed into the ice at the snow-ice transition. As the ice depth increases, the bubbles become smaller, and precise measurements of core densities show that most bubbles in deeper ice are compressed in near-equilibrium with the overburden pressure (Gow 1971a). Below about 800 m the bubbles diminish in both number and size until no trace of bubbles is found below 1100 m. This disappearance of air bubbles, which occurs *without* significant loss of air from the ice, is attributed to pressure-induced diffusion of gas molecules into the ice (Miller 1969, Gow 1971a, Gow and Williamson 1975).

A marked improvement in the condition of cores accompanies the elimination of pressurized air bubbles from the ice. Bubble-free ice lacks the brittle fractures that characterize cores of bubbly ice, especially those from 400 to 900 m. This disappearance of bubbles from the ice occurs more or less simultaneously with the formation of a vertical c-axis fabric, which seems also to have contributed to the improved condition of the cores (Gow 1971a). Such observations serve to

65 m   193 m   470 m

638 m   906 m   1137 m
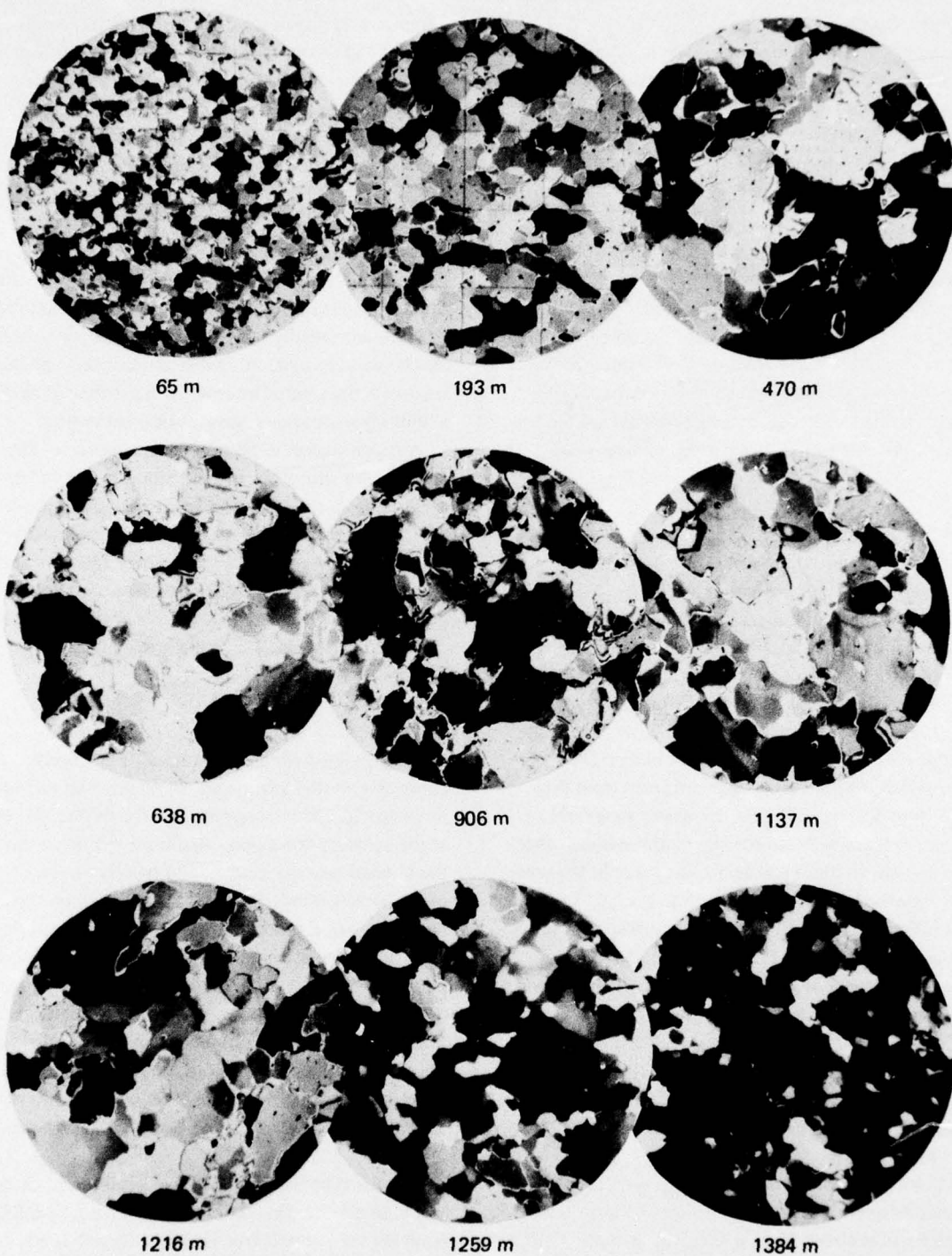
1216 m   1259 m   1384 m

Figure 2. Thin-section photographs of crystalline texture of ice in deep cores from Byrd Station. All sections were photographed between crossed polaroids at the same magnification as the two topmost sections; the grid spacing measures 1 cm. Small inclusions are air bubbles.

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1632 m   1688 m   1833 m

2046 m   2138 m
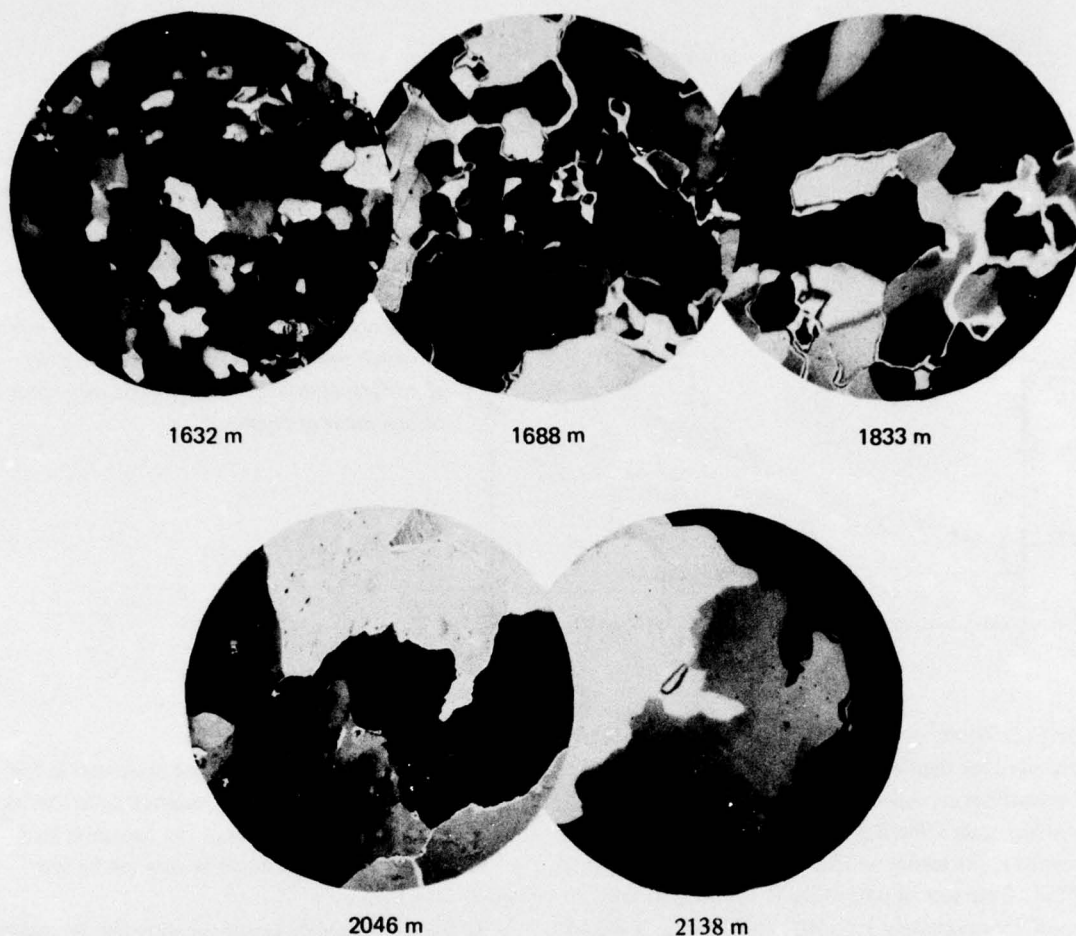
Figure 2 (cont'd).

demonstrate the extent to which the intrinsic mechanical properties of deep drill cores, e.g., ductility, are affected by changes in the texture and fabric of the ice. These properties of deep ice cores, and their relaxation with time, are discussed more fully in Gow (1971a).

Crystal size variation

Crystal size variations with depth in the ice sheet at Byrd Station are presented in Figure 3. Major features of this profile (A-D) are:

A. An approximate 20-fold increase in the average cross-sectional area of from 0.03 cm^2 at 56 m to a "limiting" size of about 0.60 cm^2 at 600 m.

B. Maintenance of a virtually constant crystal size between 600 and 1200 m.

C. A marked 2- to 3-fold decrease in crystal size between 1200 and 1300 m, with the maintenance of a fine-grained texture to a depth of more than 1800 m, in which crystal cross sections rarely exceed 0.30 cm^2. However, interdigitations of coarse-grained ice appear initially at about 1670 m. This zone of fine-grained ice is also associated with widespread volcanic dust, occurring in bands up to 6 cm thick.

D. Complete transformation to coarse-grained ice below 1810 m. Crystal cross sections in excess of 30 cm^2 are not uncommon in cores from the bottom 350 m of ice at Byrd Station.

Time-dependence of crystal growth

The mean cross-sectional area of crystals in the Byrd Station ice cores increases from 0.03 cm^2 at

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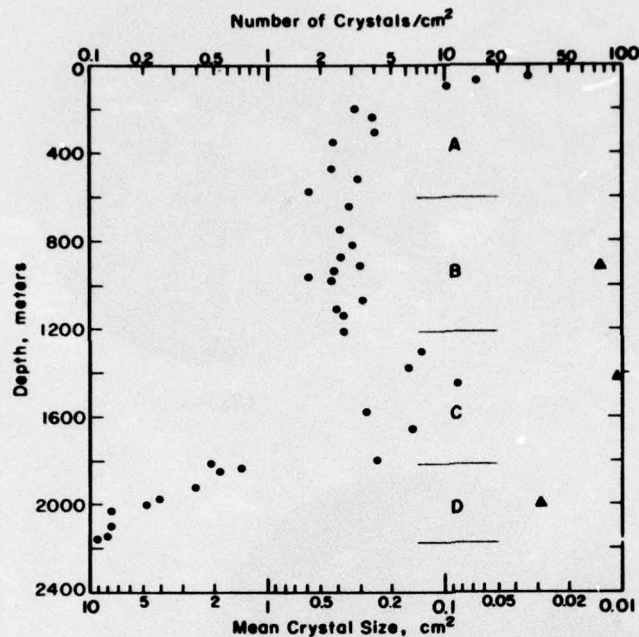Figure 3. Plot of crystal size versus depth in the Antarctic Ice Sheet at Byrd Station. Triangles denote crystal size in ultra-fine-grained ice in three volcanic dust bands. Zone A shows substantial crystal growth; Zone B shows constant crystal size, passing into Zone C, which shows ice of much smaller crystal size; Zone D defines the region of very rapid enlargement of crystals.

56 m to 0.59 cm² at 576 m. If the ages of samples are substituted for depths, then an essentially linear relation between mean crystal size and ages is obtained (Fig. 4).* These new data effectively extend the crystal size measurements made earlier on Old Byrd Station cores (Gow 1970b). Both sets of data indicate comparable growth rates of approximately 1.1×10^{-4} cm²/yr, and it would appear from these latest measurements that time-linear crystal growth is maintained to a depth of nearly 600 m, equivalent to an estimated growth time of more than 5000 years.

A near-constant crystal size between 600 and 1200 m is not associated with any thermal effects in the ice, since temperatures remain substantially isothermal throughout this depth interval. However, increased confining pressure and/or shear deformation in the ice could have inhibited crystal growth between 600 and 1200 m. Evidence in support of increased shearing includes an increase in crystals exhibiting "strain shadows" and a progressive reorienting of crystallographic c-axes into a broad single maximum by the 1200-m depth.
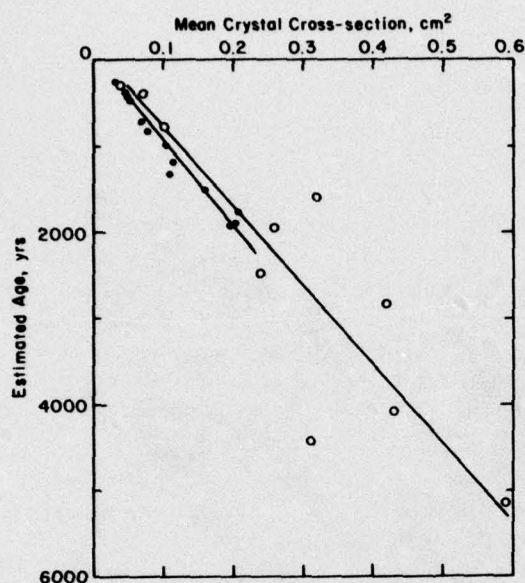
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* These ages are simply "best estimates" calculated from current rates of snow accumulation (0.13 m/yr), a constant ice thickness of 2164 m, and a simplified model of ice flow as outlined by Nye (1963) and Bader (1962).

Crystal fabrics

Representative c-axis fabrics are presented in Figure 5. The center of the fabric diagram coincides in all cases with the vertical axis of the core as drilled.

Major features of the fabric profile can be summarized as follows:

1. Ice from directly below the snow/ice boundary at 56 m features a thoroughly random fabric that is retained to a depth of at least 100 m. Some evidence exists for a 2- to 3-maximum pattern occurring as early as 160 m and some reduction of low-lying c-axes is apparent in most fabrics between 160 and 400 m. However, a preferred orientation of c-axes is not strongly developed at this stage, despite an approximate 10-fold increase in crystal size. C-axis densities rarely exceed 5% per 1% area of the stereogram, and the fabrics, overall, are similar to those observed in cores from the earlier drilling at Old Byrd Station (Gow 1970b).

2. A trend toward a broad central clustering of axes first appears between 400 and 600 m. This pattern persists to approximately 1000 m. Typically, the crystal axes are grouped into 2 or 3 maxima within 20 to 40° of the center of the stereogram, and individual maxima may now contain c-axis concentrations of up to 10% per 1% area.

3. The first sign of a single, but elongate, maximum appears at 957 m. This fabric splits into a 2-maximum

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Figure 4. Plot of crystal size versus estimated age of ice in top 500 m of ice sheet at Byrd Station. Solid circles represent data from the 308-m deep hole at Old Byrd Station (after Gow 1970b).

pattern at 1067 and 1137 m and reverts to a single-maximum fabric at 1210 m. The centers of symmetry of these and deeper fabrics are all displaced from the vertical core axis (center of the fabric projection) by 10 to 15°. Their displacements are about equal to the inclination of the drill hole itself, which would imply that the crystallographic c-axes are trending toward a vertical position in the ice sheet.

4. The c-axis fabric at 1210 m shows that crystal axes are now clustered much more tightly than in the fabric at 957 m. This clustering of c-axes transforms abruptly (between 1200 and 1300 m) into a tight single-pole fabric in which very few crystal axes deviate by more than 20° from the vertical. The establishment of a tight single-pole fabric was also accompanied by a 2- to 3-fold decrease in the size of crystals.

Axial fabrics of the kind observed at 1302 m persist to a depth of more than 1800 m. C-axis concentrations of nearly 50% in a 1% circle observed in some sections are among the strongest ever recorded in glacial ice. The only comparable fabrics are those reported by Rigsby (1960) from the Greenland ice sheet near Thule, by Hooke (1973) from the Barnes Ice Cap, and by Anderton (1974) from the Meserve Glacier, Antarctica. In these fabrics the center of the c-axis maximum generally coincides with the pole to the foliation plane or plane of implied shear. Similar but less dense single-maximum fabrics have also been reported by Hooke (1970) from Greenland, and by Lorius and Vallon

(1967) and by Budd (1972) from the edge of the Antarctic Ice Sheet. These and the broad single-maximum fabrics occasionally observed in fine-grained ice in temperate glaciers (e.g., Kamb 1959) are considered typical of ice undergoing rapid mechanical plastic flow. A strong vertical c-axis fabric has also been reported by Barkov (1973) from a depth of 494 m in the east Antarctic Ice Sheet.

The vertical alignment of crystallographic c-axes in single-maximum fabrics at Byrd Station is made even clearer in thin sections from the interval between 1302 and 1570 m. These sections are oriented carefully with respect to volcanic dust bands that are inferred, from inclinometer measurements, to occur horizontally in the ice sheet. In each of the 5 fabric sections from 1302 to 1570 m (Fig. 5), the center of the c-axis [0001] maximum coincides almost exactly with the pole to the plane of banding, which simply implies that the basal glide planes (0001) of crystals here are oriented substantially parallel to the horizontal plane of the ice sheet.

5. Although fine-grained ice of the kind exhibiting single-pole fabrics persists to about 1810 m (the last single-maximum pattern was measured at 1804 m), some intermixing of coarse- and fine-grained ice was observed as high as 1610 m. These interdigitations of coarse- and fine-grained ice were also accompanied by fabric reversals in which the strong single maximum

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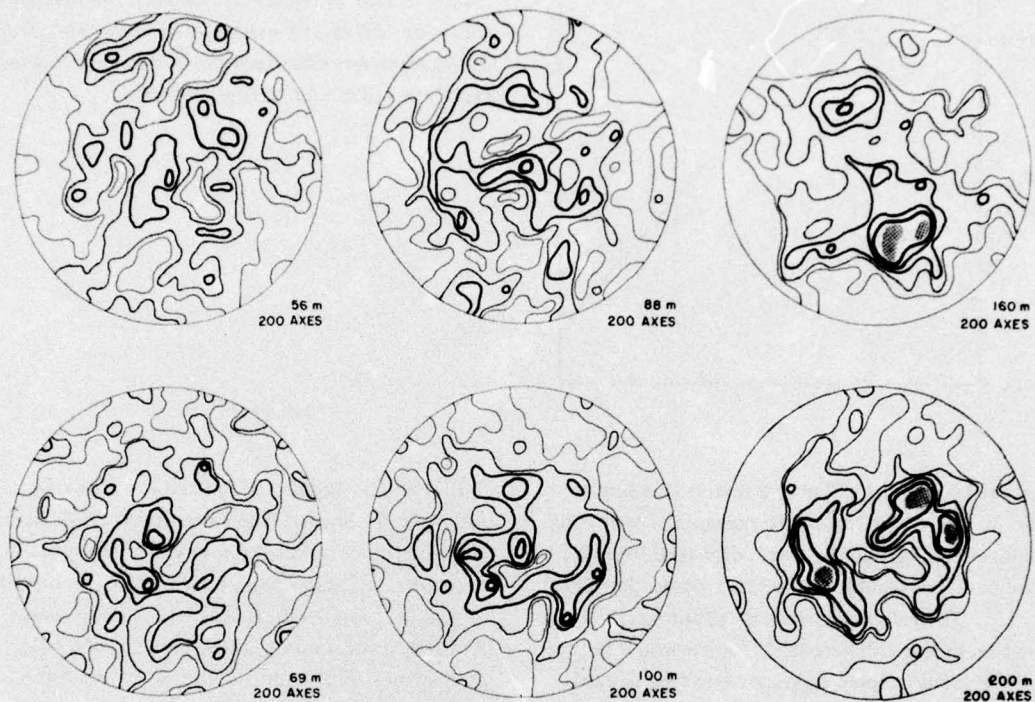
Figure 5. C-axis fabrics profile through the Antarctic Ice Sheet at Byrd Station. All fabrics were obtained from sections normal to the long axis of the cores. The trace and pole of cloudy bands (volcanic dust) are included in several diagrams for ice from the zone of single-maximum fabrics.

Contour Intervals

Sections from 56 m to 906 m: 5, 4, 3, 2, 1 and ½% per 1% area.
Sections from 957 m to 1137 m: 10, 5, 4, 3, 2 and 1% per 1% area.
Sections from 1210 m to 1804 m: 25, 20, 15, 10, 5, 2 and 1% per 1% area.
Sections from 1833 m to 2154 m: 10, 5, 4, 3, 2 and 1% per 1% area.

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240 m
200 AXES

439 m
140 AXES

638 m
151 AXES

957 m
200 AXES

300 m
200 AXES

470 m
137 AXES

760 m
165 AXES

1067 m
160 AXES

340 m
162 AXES

508 m
150 AXES

867 m
198 AXES

1137 m
152 AXES

400 m
152 AXES

576 m
126 AXES

906 m
180 AXES

1210 m
200 AXES

957 m
200 AXES

1259 m
200 AXES

1487 m
200 AXES

1736 m
200 AXES

18
200

1067 m
160 AXES

1302 m
200 AXES

1570 m
200 AXES

1794 m
200 AXES

1958
200

1137 m
152 AXES

1382 m
200 AXES

1634 m
200 AXES

1804 m
200 AXES

20
20

1210 m
200 AXES

1458 m
200 AXES

1689 m
123 AXES

1833 m
200 AXES

1259 m
200 AXES

1487 m
200 AXES

1736 m
200 AXES

1877 m
200 AXES

2097-
2102 m
154 AXES

1302 m
200 AXES

1570 m
200 AXES

1794 m
200 AXES

1958-60m
200 AXES

2151-54m
138 AXES

1382 m
200 AXES

1634 m
200 AXES

1804 m
200 AXES

2012-14 m
200 AXES

1458 m
200 AXES

1689 m
123 AXES

1833 m
200 AXES

2045-48m
200 AXES

3

Figure 6. C-axis fabric profile for the Ross Ice Shelf at Little America V, Antarctica. All fabrics were obtained from horizontally sectioned cores. Contours at 10, 5, 4, 3, 2 and 1% per 1% area of the projection.

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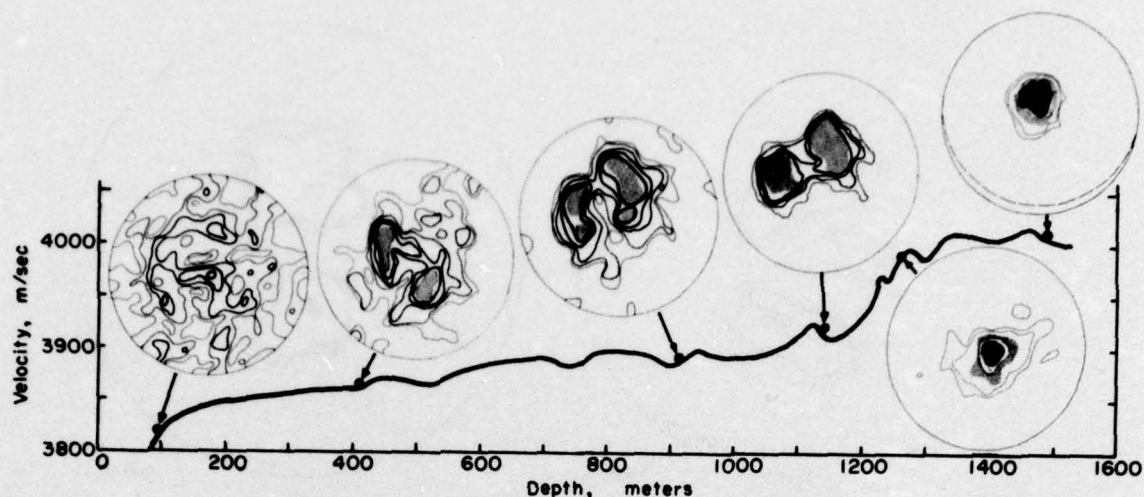
Figure 7. Correlation of ice fabrics and p-wave velocity profile from the drill hole at Byrd Station. Velocity profile was adapted from Bentley (1972). Peak velocity correlates with vertical c-axis fabric.

of the fine-grained ice was replaced by a multiple-maximum fabric in the coarse-grained ice. This reversal is exemplified in the fabric of coarse-grained ice from 1689 m.

6. Below 1810 m the cores are composed entirely of coarse-grained ice in which the fabrics, without exception, are of the multiple-maximum type. Although some variation in the distribution of maxima is observed, none of the individual maxima deviate by more than 45° from the center of fabric symmetry.

The fabric at 1833 m and 1877 m is quite similar to that measured at 1689 m, but in deeper ice a new pattern begins to emerge in which the individual maxima tend to form a ring around the vertical. This ring-like arrangement of maxima is a distinctive fabric, since very few c-axes occur inside or outside the ring. The pattern is quite different from the 2- and 3-maximum fabrics associated with the broad central clustering of c-axes in ice from between 600 and 1200 m.

The textures and ring-maximum fabrics of the bottom cores from Byrd Station are similar to those observed by Gow (1970b) in deeper parts of the Ross Ice Shelf at Little America V, Antarctica (Fig. 6). In both cases ring-maximum fabrics are best developed in ice close to the melting point. The same ice also contains the largest crystals, which might suggest that temperature is a dominant factor in recrystallization of bottom ice at Byrd Station.

Correlation of seismic and crystal anisotropy

During 1969-70 Bentley (1972) conducted measurements of ultrasonic p-wave velocity in the Byrd Station drill hole. Although measurements could be conducted only to a depth of 1540 m, because of a blockage in the hole just below this level (Hansen and Garfield 1970), the velocity profile clearly confirmed the existence of a strong vertical c-axis orientation that had been anticipated on the basis of preliminary fabric studies first reported by Gow et al. (1968). Apart from the sharp initial increase in p-wave velocity in the top 200 m, which can be attributed largely to increasing ice density, virtually all subsequent velocity increase is consistent with the pattern of crystal fabric changes and transitions reported here. This correlation (Fig. 7) is especially significant with respect to the abrupt increase in p-wave velocity between 1200 and 1300 m. This increase, which actually exceeds the total velocity increase observed in the preceding 1000 m (200 to 1200 m), agrees almost perfectly with the onset and attainment of a tight clustering of c-axes about the vertical. The subsequent leveling off of the velocity to a near-constant value below 1300 m can be correlated equally well with the establishment of a very tight single-maximum fabric.

Velocities computed from the observed fabrics (Bentley 1972) agree fairly well with those logged downhole. A few discrepancies were noted, however, that could be linked to volume orientation effects

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that were not considered in the velocities calculated from fabrics. This possible dependence of the fabric on crystal size, as observed in thin sections, has been evaluated at several representative levels in the ice sheet at Byrd Station (Fig. 8). In each of the fabrics tested, all crystals larger than 2 times the mean crystal cross section were plotted separately. These larger crystals generally constituted no more than 10% of the total number of crystals measured, but they could constitute as much as 40% of the total area of crystals. Except for a possible dependence of orientation on crystal size at 300 m, it would appear that the c-axis orientations of the larger crystals do not depart significantly from the general pattern of distribution of c-axes in any of the fabrics investigated. This absence of an obvious relation between crystal size and fabric suggests that the growth of larger crystals is not simply due to crystals of some "set" orientation absorbing neighboring crystals and imposing their orientation on the new structure.

DISCUSSION

The vertical section of core at Byrd Station indicates that changes in the texture and/or fabric of the ice have occurred simultaneously with deformation. In addition to directed stress or shear, other factors that could be expected to have shaped the course of crystallization (and recrystallization) include the overburden pressure, temperature of the ice, and time.

Factors affecting recrystallization

Variations in temperature, ice load and age with depth in the ice sheet are given in Figure 9. Temperature in the ice remains essentially constant to 900 m and then increases progressively with depth until it reaches the pressure melting point at the ice rock interface. Measurements of overburden pressure, calculated from density data, show that ice load increases linearly with depth, attaining a value of 193 bars at the bed. This pressure is sufficient to depress the melting point of the ice to $-1.7°C$. As noted previously, the age of the ice can be estimated only on the basis of assumptions that indicate that age should increase exponentially with depth and that the bottom ice could be

as old as 100,000 years (Epstein et al. 1970).* Although no precise measurements of shear or its variation with depth at Byrd Station are available, the location of Byrd Station on the thick inland ice of Antarctica probably means that the longitudinal strains are small; according to Budd (1972), horizontal shear could be expected to become dominant at depth.

Recrystallization in the top 1200 m

Recrystallization throughout the top 400 m at Byrd Station involves changes mainly in the shapes and sizes of crystals, especially crystal cross-sectional areas, which increase approximately 10-fold between 56 m and 400 m. Since these pronounced changes in texture in the top 400 m at Byrd Station are not accompanied by any substantial increase in c-axis orientation, it would appear that this stage of isothermal recrystallization is concerned largely with minimization of surface free energy, which it accomplishes by a process of normal grain (crystal) growth.

The observed linear increase in crystal size with age conforms precisely with the time-linear growth relationship established for isothermal grain growth in metals, e.g., Burke and Turnbull (1952), where the driving force for such growth is now generally attributed to the interfacial free energy of the grain boundaries. The ice textures also simulate those found in rocks that have recrystallized under low to moderate confinement pressures in the earth's crust, e.g., quartzites.

Only a small increase in crystal size is observed between 400 and 600 m, suggesting either that normal grain growth is coming to an end or that other factors are beginning to influence the course of recrystallization. A definite pattern of preferred orientation of ice crystals also begins to appear between 400 and 600 m.

No significant increase in crystal size was observed between 600 and 1200 m. However, the increased tendency for the c-axes of crystals to cluster into one or more maxima about the vertical clearly demonstrates that recrystallization is still occurring, but that most of the energy of recrystallization is being expended in the formation of an oriented crystal structure. The nature of the fabric indicates that horizontal shear is now influencing recrystallization to an increasing degree. For example, the fabric at 957 m is compatible with a

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Thompson (1973), using data based on dust particle counts in the cores, suggests that the ice near the bottom of the drill hole at Byrd Station may be no older than 27,000 years. The discrepancy between this

estimate and that of Epstein et al. (1970) simply points up the urgent need for some means of determining absolute ages of deep ice cores.
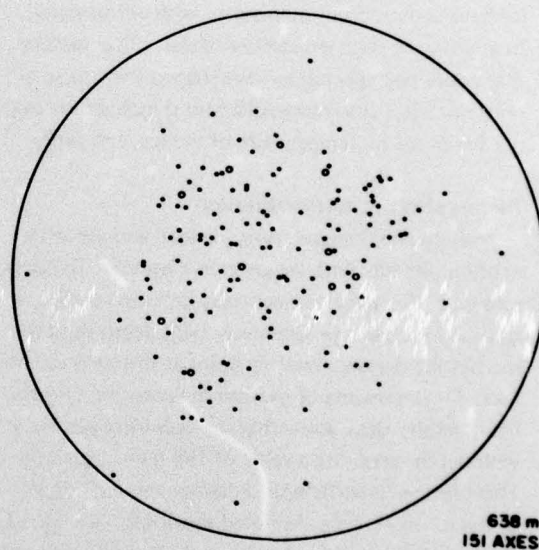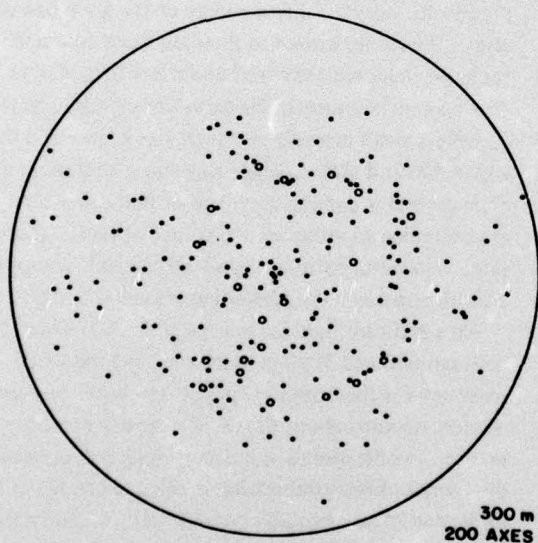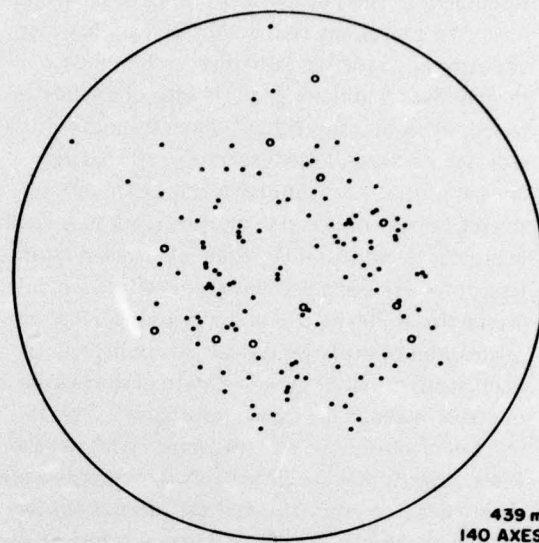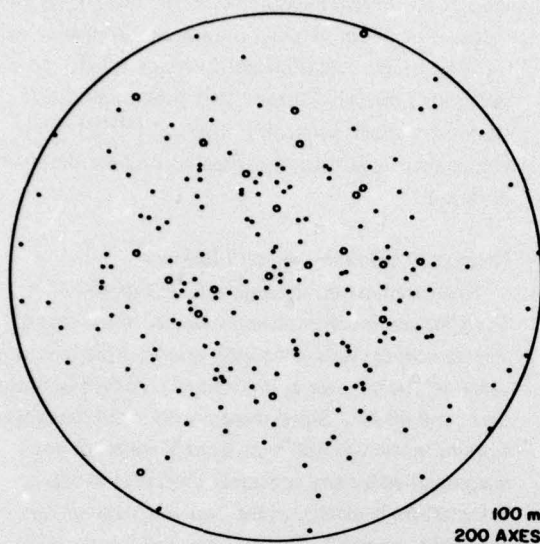
Figure 8. C-axis plots for determining if significant volumetric orientation effects exist in ice at Byrd Station. Crystals measuring more than twice the mean size of crystals in the section are plotted as open circles. No strong relation between crystal size and c-axis orientation is indicated, except possibly at 300 m.

14
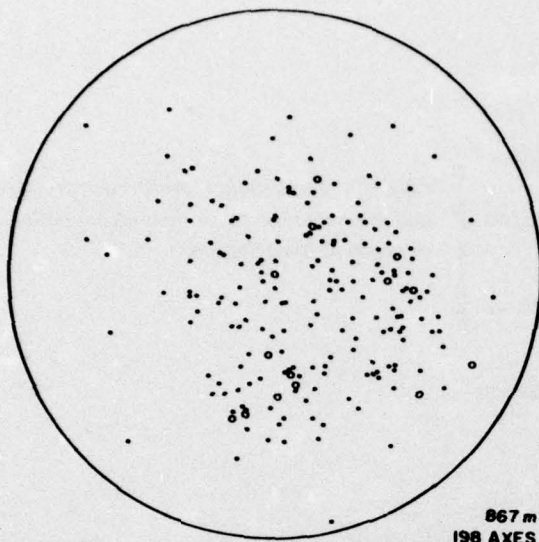
867 m
198 AXES
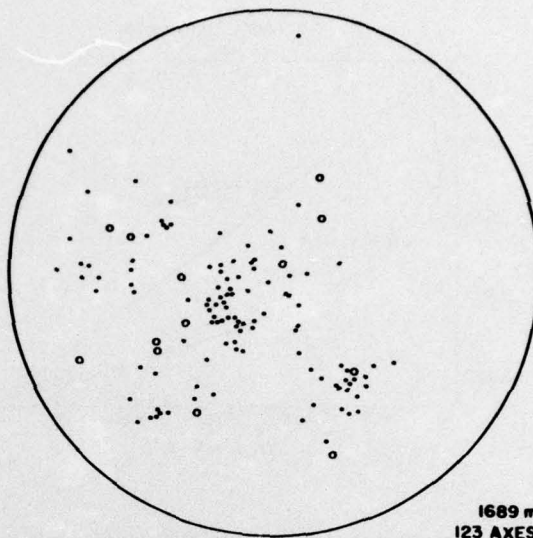
1689 m
123 AXES
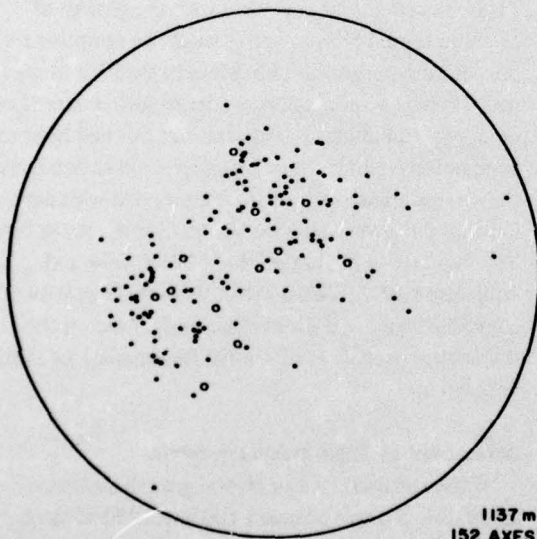
1137 m
152 AXES
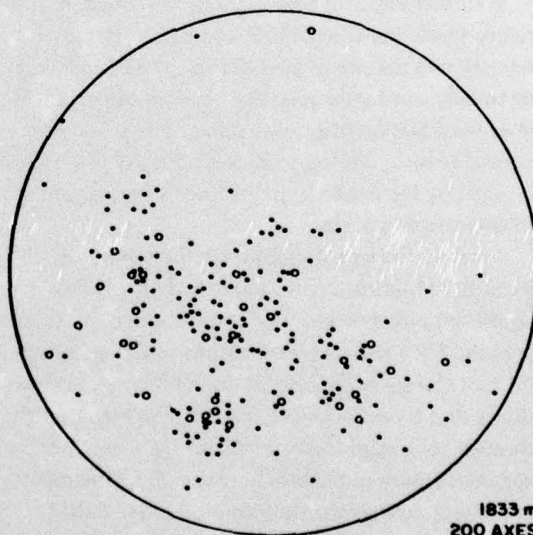
1833 m
200 AXES

Figure 8 (cont'd).

15
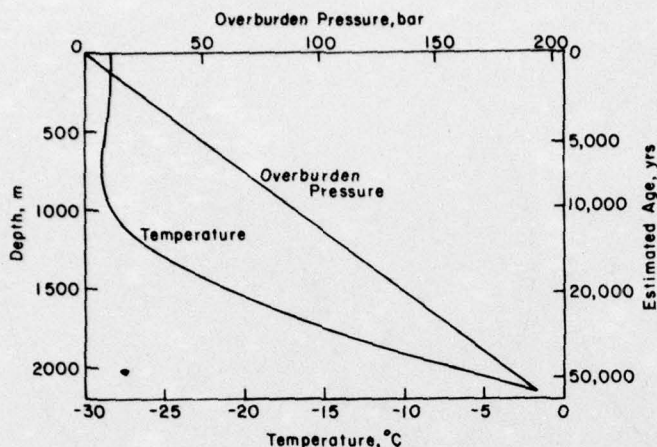
Figure 9. Temperature, overburden pressure and estimated age of ice sheet as a function of depth at Byrd Station.

process of reorientation of crystal glide planes (0001) into the plane of maximum resolved shear.*

Additional evidence of increased shear strain in the ice between 600 and 1200 m at Byrd Station is provided by the widespread occurrence in "strained" crystals of extinction bands parallel to the c-axis. Such bands are herein attributed to "kinking" by slip on the basal glide planes of the ice crystals.

A further effect of shearing, amply verified in laboratory studies by Glen (1955) and Rigsby (1960), is a reduction in the size of pre-existing crystals. Thus, an essentially constant crystal size between 600 and 1200 m at Byrd Station might well reflect a situation where normal growth, tending to increase the size of crystals, is offset by the mechanical effects of shearing, acting to decrease crystal size.

An abundance of air bubbles in the top 800 m of ice at Byrd Station seems to have had little if any significant effect on recrystallization, especially crystal growth. Such growth is not accompanied by any significant change in the distribution of bubbles, which shows that crystal boundaries are able to migrate right through the bubbles without disturbing them. This apparent failure of bubbles to inhibit grain boundary movement during recrystallization is in agreement with the experimental findings of Kamb (1972), but

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* Weertman (1973) believes that nonbasal glide may be the rate-controlling mechanism in the flow of randomly-oriented, polycrystalline ice. While such a mechanism may apply in the upper third of the ice sheet at Byrd Station, it would seem, from the fabric patterns demonstrated here, that basal glide is dominant in deeper ice.

is at variance with the field observations of Rigsby (1960). However, the size of bubbles could be a critical factor; if such bubbles are large in comparison with the crystals, then they could conceivably interfere with grain growth. At Byrd Station the bulk of the recrystallization occurs in ice in which crystals are generally very much larger than associated bubbles.

The disappearance of air bubbles between 800 and 1100 m occurs simultaneously with the growth of oriented crystal fabrics, and it would be tempting to link this disappearance of bubbles to shearing in the ice. There is no compelling evidence such as stretched or elongated bubbles to indicate that this had been the case, however, and a more plausible explanation is that the disappearance of bubbles is associated with pressure-induced diffusion of gas molecules into the ice to form a gas hydrate or clathrate (Miller 1969, Gow and Williamson 1975). What effect this small quantity of cubically-structured gas hydrate might have on the rheological properties of normal (hexagonal) ice is not known.

Attainment of single-maximum fabrics

If the apparent lack of crystal growth and associated fabric changes between 600 and 1200 m can be correlated with increasing horizontal shear in the ice sheet, then the abrupt transformation to a single-maximum fabric between 1200 and 1300 m, and the dramatic 2- to 3-fold decrease in crystal size that accompanied it, would indicate that horizontal shear has become dominant. For example, in ice at 1302 m the basal glide planes of all crystals are aligned within

16
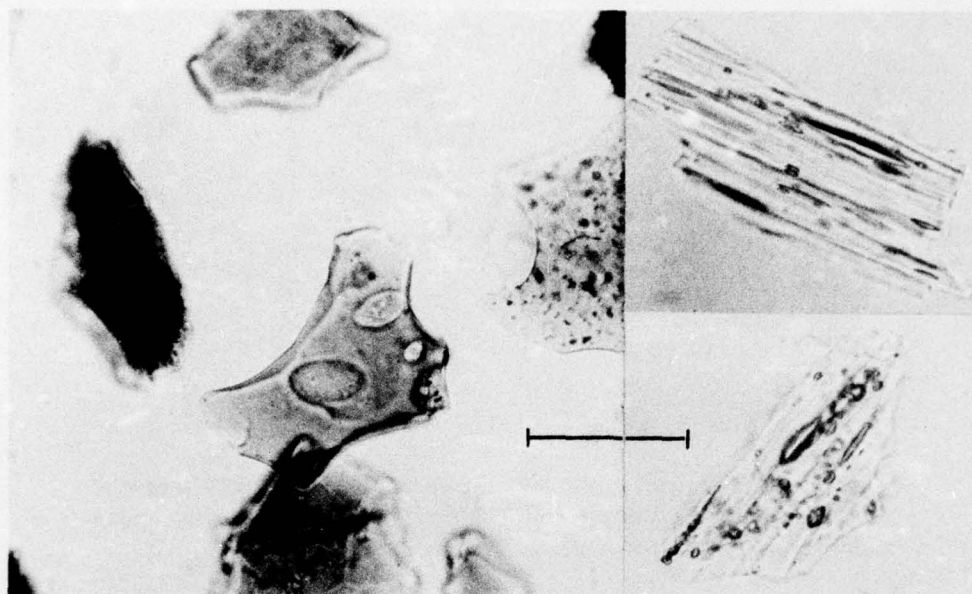
Figure 10. Glass shards from volcanic ash bands in ice cores from the Antarctic Ice Sheet at Byrd Station. The scale bar measures 50 μ.

20° of horizontal. This situation persists to at least 1800 m.*

Textures and fabrics of volcanic ash bands

Ice in the zone of sharp single-maximum fabrics (1200 to 1800 m) also contains numerous cloudy bands, ranging in thickness from 1 mm to 6 cm. Some bands contained particles large enough to be seen with the unaided eye; this debris was subsequently identified as volcanic ash (Gow and Williamson 1971). Glass shards of the kind illustrated in Figure 10 frequently constitute 75% or more of the particles in a single ash fall. Crystalline and lithic particles are also observed. Many of the particles still carry adherent glass, an excellent criterion of the direct pyroclastic origin of

this debris. However, most of the cloudy bands contain only dust composed mainly of glass particles and crystals measuring less than 5 μ.

A typical example of cloudy-band ice is shown in Figure 11. The average size of crystals in the bands is always very much smaller than that in the surrounding ice. This small size of crystals may be due, in part, to ash particles in the ice inhibiting grain growth. However, the fragmented appearance of most crystals, and widespread undulatory extinction, indicate that deformation has also contributed to the formation of a fine-grained ice texture in cloudy bands.

Composite fabrics of six ash bands are presented in Figure 12. Most of the bands examined are so fine grained (mean crystal diameters of the order 1.0 mm are not uncommon) that the conventional universal stage and microscope were needed to measure c-axis orientations. No significant differences in orientation between crystals in the band and those in the enclosing ice are evident in the section of core from the 788-m depth. This particular band marks the first appearance of volcanic ash in cores at Byrd Station. Crystal axes in the next band (910 m), however, tend to be more tightly clustered about the vertical than those in the surrounding ice. This difference in fabric was the first indication that the

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The abrupt decrease in crystal size at 1200 to 1300 m occurs more or less coincidentally with an abrupt change in the oxygen isotope ratios of the cores (Epstein et al. 1970). This change corresponds in time with the end of the last glaciation. W.S.B. Paterson (Personal communication, 1975) has suggested that the small size of crystals between 1200 and 1800 m may also reflect depositional conditions during the last glaciation when surface temperatures were much colder than at present.

17
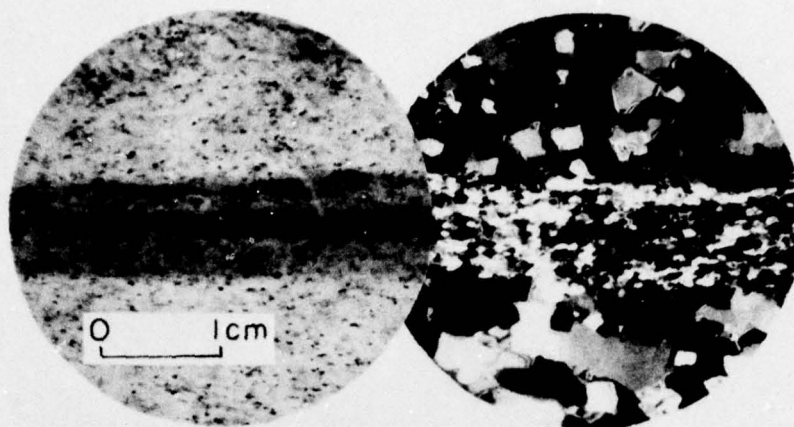
Figure 11. Representative example of a cloudy band (volcanic dust) as it appears (a) in the core and (b) in thin section. Depth 1415 m. Note that band-ice crystals are very much smaller than crystals in the unbanded ice.

788 m   910 m
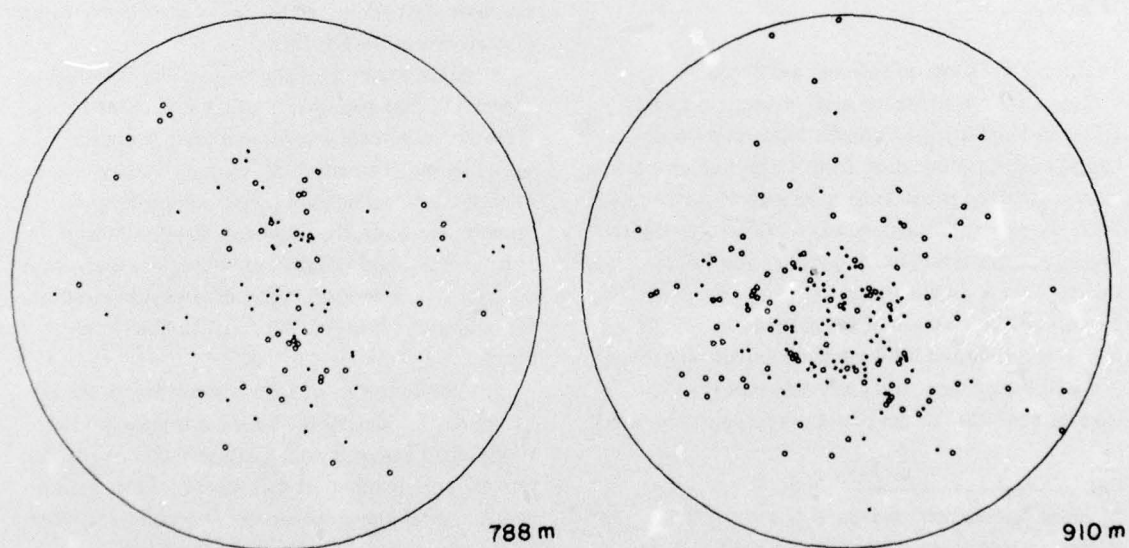
Figure 12. Composite c-axis fabrics of six cloudy bands and enclosing ice. Crystal relationships are as depicted in the thin section photograph in Figure 11. C-axes of band-ice crystals are plotted as solid circles; open circles denote crystals in the enclosing ice.

18

1310 m   1415 m

1532 m   2006 m
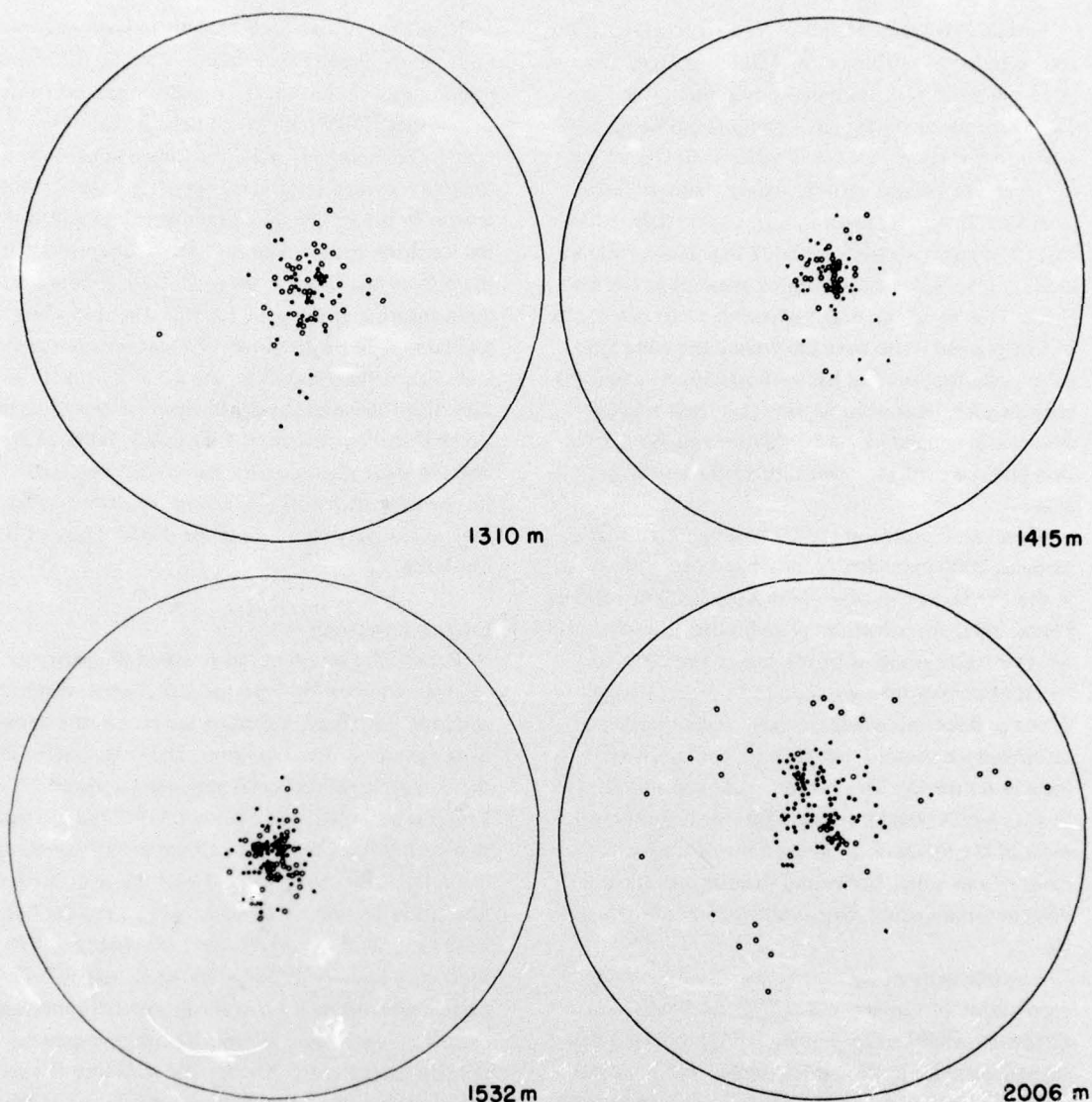
Figure 12 (cont'd).

plasticity of ice in cloudy bands may differ appreciably from that of the enclosing ice. Crystals in three successively lower bands, all from the zone of single-maximum fabrics, also display a tight clustering of c-axes about the vertical. The fabrics of both types of ice are compatible with strong horizontal shearing, and the ultrafine, fragmented appearance of crystals in the ash-bearing bands certainly suggests that such bands of very fine-grained ice may also constitute zones of actual shear displacement in the ice sheet.

Kamb (1959) has inferred a similar origin for fine-ice layers in the Blue Glacier where the c-axes of the crystals are invariably centered about the pole to the plane of implied shear. Rigsby (1958) has suggested that fine-ice textures in the more active parts of glaciers may be due to actual granulation of coarser grained ice. Such "granulated" ice is invariably associated with foliation, which, Rigsby concludes, particularly in the case of the Malaspina Glacier, is caused by shearing along closely spaced planes in the ice. The bands of fine-grained ice at Byrd Station also resemble the "shear zones" that Shumsky (1958) observed forming in ice subjected to sustained shearing in laboratory tests.

Several fine-grained bands were also observed in the coarse-grained ice from below 1800 m at Byrd Station. A case in point is the sample from 2006 m (see Fig. 12) where the enclosing ice is composed of large crystals with divergent c-axis orientations. The band ice, however, still retains a sharp single-maximum fabric. That fine-ice bands persist in highly recrystallized ice further strengthens the likelihood that such bands are actively involved in concentrated shearing in the ice sheet. Otherwise, we might have expected such bands of fine-grained ice to have undergone the same kind of recrystallization that has so drastically affected the enclosing ice. It is possible, however, that volcanic particles in banded ice have inhibited recrystallization (grain growth) by "anchoring" the crystal boundaries.

Gow and Williamson (1971) have reported that as many as 2000 individual cloudy bands were preserved in the Byrd cores, mostly in the zone 1200 to 1800 m. Petrographic investigations were limited to just a small representative group of bands, but of the 20 or so bands examined, *all* were found to contain volcanic debris of direct pyroclastic origin. Examinations of unbanded ice showed that such ice contained very little or no debris. This restriction of volcanic dust to fine-ice bands could be significant rheologically, since *most of the bands occur in the zone of single-maximum fabrics* where horizontal shearing has apparently become a dominant factor in the deformation of the ice.

The plasticity of ice may be increased by the incorporation of fine-grained debris. Butkovich and Landauer (1959) and Swinzow (1962) reported that slightly dirty ice in the TUTO tunnels in Greenland deforms more readily than clean ice. This appears to be especially true of those silt bands in which grain-to-grain contacts are minimized. Measurements by J. Abel [results reported in Swinzow (1962)] also show that some silt bands in the TUTO tunnels coincide with surfaces of concentrated differential movement. Laboratory investigations appear to have been restricted to observations of the creep characteristics of sand-ice systems (Hooke et al. 1972, Goughnour and Andersland 1968). Hooke et al. (1972) found that creep rates in ice with low sand concentrations were in some cases higher, and in other cases lower, than in clean ice. This aspect of ice rheology clearly merits further detailed study, but it appears from field observations that small amounts of dust-sized particles in glacier ice may enhance its deformation.

If, as the evidence indicates, there is displacement of ice along discrete shear planes at many different levels in the ice sheet at Byrd Station, then current theories regarding the flow of large ice masses may need to be modified. Most theories assume isotropic structure throughout the ice, which is clearly at variance with the highly anisotropic state of crystals in the ice sheet at Byrd Station. The assumption that the bulk of the flow occurs by bottom sliding and/or rapid shearing of the basal ice will also need to be revised in light of the strong orientation anisotropy and evident shearing within the ice at Byrd Station. Any disturbance of the depth-age relationship of the ice by shearing, especially differential sliding along discrete shear planes, could also distort englacial stratigraphy such as stable isotope records that are used extensively for probing the climatic history of ice sheets.

Internal reflections

Radio-echo sounding has revealed the existence of extensive layering (internal reflections) within the Antarctic Ice Sheet, including the area in the immediate vicinity of Byrd Station. The exact nature of these internal reflections is still being pondered. Robin et al. (1969) and Harrison (1973) suggested that such echoes could result from variations in either the density, dirt content or crystal fabric of the ice. Internal reflections were observed to a depth of at least 1350 m in the original records obtained at Byrd Station in January 1968 (Robin et al. 1970).[*] A particularly strong echo at about 1250 m appears to correlate with a layer of volcanic ash; the same reflection can be correlated equally well with the establishment of a strong vertical c-axis fabric at this depth. However, density variations at this depth seem much too small to account for this reflection.

Harrison (1973) tends to favor crystal anisotropy as the most likely cause of internal reflections, though he also suggests that the denser ash layers may be responsible for some reflections. Paren and

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* Records obtained in January 1975 with improved equipment show more numerous and deeper echoes than were observed in the original records. These later records are now being investigated for possible correlation of internal layering with volcanic ash and dust band distribution and crystal fabric variations in the ice cores.

Robin (1975) do not believe, on the basis of the observed echo strengths, that isolated layers of dirt or dust are capable of producing internal reflections, but suggest instead that they are due to systematic fluctuations of density, crystal anisotropy or loss tangent. However, the Byrd Station ice cores contain large numbers of closely spaced dust bands (25 or more per meter in some core sections) that, acting together, might give rise to a detectable reflection. The fact that the crystalline texture and fabric of these bands is compatible with zones or surfaces of shearing might be further reason to suspect closely grouped bands as potential sources of internal reflections.

Recrystallization in the bottom 350 m

The rapid transformation to coarse-grained ice with multiple-maximum fabrics below 1810 m constitutes a major change of structure that we attribute more to the overriding effects of age and rapidly increasing temperature than to any drastic decrease in stress below 1810 m. Temperature increases from $-15°C$ at 1810 m to $-1.7°C$ (pressure melting value) at 2164 m, which is equivalent to an average temperature gradient of nearly $0.04°C/m$. The age of the ice as estimated by Epstein et al. (1970), increases from 30,000 years to nearly 100,000 years in the same interval. Thus, the ice in the bottom 350 m at Byrd Station is both the oldest and the warmest, and recrystallization under these conditions would favor the growth of large crystals.

Recent examination of some of the deeper ice cores from below 1800 m has disclosed the existence of a fine-grained "mosaic" texture etched onto the surfaces of cores. This surface texture is due either to thermal etching or to the sustained etching action of drill-hole fluids that tend to persist in a film on the exposed surfaces of cores. The mean size of the "mosaic" grains is generally an order of magnitude smaller than the crystals observed optically in thin sections of the same cores. Since the "mosaic" grain size is comparable with crystal dimensions observed in the zone of fine-grained ice at 1200-1800 m, this might suggest that the "mosaic" texture in cores of etched coarse-crystal ice below 1800 m is a relic of the texture that existed prior to recrystallization. Very similar surface "mosaic" textures have also been observed in etchings of very coarse-grained ice in cores from the edge of the Greenland ice sheet (Colbeck and Gow 1974).

Cores from the bottom 5 m of ice at Byrd Station contain so much morainal debris that it was not possible to measure c-axis fabrics in this ice. Evidence based on ice-dirt stratigraphy, the stable isotope composition of the ice and its entrapped-air content (Gow and Williamson 1975), indicates that this bottom ice originated by the freezing-on of meltwater at the bed and that the morainal debris, ranging in size from clay particles to cobbles, was incorporated at the same time. The mechanics of such a process have been fully elaborated by Weertman (1961). Water was observed entering the drill hole soon after the ice/rock interface was penetrated, indicating that bottom melting rather than freezing is currently occurring in the immediate vicinity of the drill hole at Byrd Station. Some basal sliding could be expected to occur under these conditions.

Sonic logging of the drill hole at Byrd Station (Bentley 1972) also confirms the existence of a strong vertical alignment of crystallographic c-axes in the lower half of the ice sheet. Bentley (1971), using seismic records, has also demonstrated the existence of highly anisotropic crystal structure throughout much of the west Antarctic Ice Sheet. Such crystal anisotropy, which appears to be related to the large-scale flow patterns in the ice sheet, could involve as much as 90% of the ice column in some parts of west Antarctica. Oriented crystal structure at Byrd Station exists to within 400 m of the surface of the ice sheet and thus represents about 80% of the ice column in the immediate vicinity of the drill hole.

CONCLUSIONS

Single crystals of ice respond readily to shear by gliding on the basal plane (0001). Where ice crystals are restrained at grain boundaries, basal gliding is facilitated by bending or buckling of glide planes. It is mainly for these reasons that the basal planes of crystals in the more actively deformed parts of glaciers tend to become oriented within the plane of maximum resolved shear. Shear planes inferred from the glacier fabric can be correlated commonly with planar structures called foliation. However, fabrics with c-axes [0001] clustered in a single maximum about the pole to the foliation are commonly supplanted by multiple-maximum patterns in which the c-axes are clustered into several discrete maxima about the pole to the shear plane. Multiple-maximum fabrics occur in polar as well as temperate glaciers, but just why multiple-maximum fabrics should form under conditions that

would appear to favor single-pole fabrics is not fully understood. Neither temperature nor stress appears to exert any exclusive control on the formation of multiple-maximum fabrics in glacier ice.

Evidence suggests that single-maximum fabrics are restricted to the more intensely sheared parts of glaciers, temperate and polar. Such fabrics are consistent with a process of rapid mechanical plastic deformation dominated by glide on the basal planes of the ice crystals. This view is supported by the observed strong relationship of the fabric (glide plane orientation) to the plane of measured or inferred shear. The generally fine-grained state and the optically-strained nature of crystals in ice exhibiting single-maximum fabrics are also compatible with strong shearing.

Single-maximum fabrics in cold polar ice such as that found at Byrd Station tend to consist of tightly clustered axes (c-axis densities of 30% per 1% area not uncommon in this kind of ice), whereas in temperate glaciers the c-axis concentrations rarely exceed 10% per 1% area. This broader spread of axes in temperate ice might be related to greater molecular mobility, which should be at a maximum in temperate glaciers where temperatures are either at the melting point or close to it. This view is consistent with Kamb's (1959) inference that layers of fine-grained ice with single-maximum fabrics in temperate glaciers generally coincide with zones undergoing rapid mechanical plastic flow; adjacent layers of coarse-grained ice, featuring multiple-maximum fabrics, are believed to originate by recrystallization of fine-grained ice not now deforming by rapid plastic flow.

The multiple-maximum patterns observed in ice, both above and below the zone of single-maximum fabrics at Byrd Station, demonstrate that a single-pole fabric can either derive from, or be transformed into a multiple-maximum fabric. The multiple-maximum pattern in ice above the zone of single-pole fabrics at Byrd Station, however, has more in common with the broad single-maximum type of fabric than it does with the "typical" 3-and 4-maximum pattern observed in ice directly beneath the zone of single-maximum fabrics. A ringlike distribution of c-axes is especially characteristic of ice in the bottom 200 m at Byrd Station.

The apparent relationship of crystal size to fabric pattern indicates that single-maximum fabrics are invariably associated with fine-grained ice undergoing rapid shearing, whereas multiple-maximum fabrics are almost always associated with coarse-grained ice. At Byrd Station rapidly increasing temperature and age are both apparently involved in the transformation (recrystallization) from a single-maximum to a multiple-maximum fabric.

A transitional fabric may be represented in coarse-grained ice that interdigitates with fine-grained ice between 1670 and 1810 m. The fabric of coarse-crystal ice is definitely of multiple-maximum type, but it still retains the strong central maximum, reminiscent of the single-maximum fabric of the fine-grained ice that incloses the zones of coarse-grained ice.

The flow of ice sheets is generally attributed to a combination of bottom sliding and shearing concentrated in the basal layers of ice. Some slipping of ice along the bedrock seems likely at Byrd Station since liquid water is known to exist at the ice/rock interface. However, the textures and fabrics of the ice cores indicate that both plastic deformation (intracrystalline gliding) and movement of ice along horizontal shear planes well above the bed are also major contributors to the flow of the west Antarctic Ice Sheet at Byrd Station. Any significant displacement of ice within the zone of shear (1200 to 1800 m) at Byrd Station could disturb the depth-age relationships sufficiently to distort stratigraphic records contained in the ice cores, such as climatic history based on stable isotope analyses. Also, the current practice of approximating the ages of cores on the basis of simplified flow models tends to ignore the orientation anisotropy in the ice. If the situation at Byrd Station is at all representative of thick ice sheets, then the need for similar petrographic studies of all deep glacier ice cores cannot be overemphasized.

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